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Monitoring *Chandra* observations of the quasi-persistent neutron-star X-ray transient MXB 1659–29 in quiescence: the cooling curve of the heated neutron-star crust

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ABSTRACT

We have observed the quasi-persistent neutron-star X-ray transient and eclipsing binary MXB 1659–29 in quiescence on three occasions with *Chandra*. The purpose of our observations was to monitor the quiescent behavior of the source after its last prolonged (∼2.5 years) outburst which ended in September 2001. The X-ray spectra of the source are consistent with thermal radiation from the neutron-star surface. We found that the bolometric flux of the source decreased by a factor of 7–9 over the time-span of 1.5 years between our first and last *Chandra* observations. The effective temperature also decreased, by a factor of 1.6–1.7. The decrease in time of the bolometric flux and effective temperature can be described using exponential decay functions, with e-folding times of ∼0.7 and ∼3 years, respectively. Our results are consistent with the hypothesis that we observed a cooling neutron-star crust which was heated considerably during the prolonged accretion event and which is still out of thermal equilibrium with the neutron-star core. We could only determine upper-limits for any luminosity contribution due to the thermal state of the neutron-star core. The rapid cooling of the neutron-star crust implies that it has a large thermal conductivity. Our results also suggest that enhanced cooling processes are present in the neutron-star core.

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1. Introduction

Neutron stars in low-mass X-ray binaries accrete matter from solar mass companions. Among those systems, the sub-group of neutron-star transients spend most of their time in quiescence during which hardly any or no accretion occurs. However, these transients sporadically become very bright ($>10^{36-38}$ erg s^{-1}) owing to a huge increase in the accretion rate onto their neutron stars. During those outbursts, these sources can be readily studied with the available X-ray instruments, but obtaining high quality quiescent data remains a challenge. In spite of this, several systems have now been studied in detail: they typically exhibit 0.5–10 keV luminosities of 10^{32-33} erg s^{-1} and their spectra are usually dominated by a soft component which can be described by a thermal model. This emission is thought to be due to the cooling of the neutron star which has been heated during the outbursts (Brown, Bildsten, & Rutledge 1998; Campana et al. 1998a).

Most neutron-star transients are active for only weeks to months, but several systems have remained active for years and even decades (the 'quasi-persistent' neutron-star transients; Wijnands et al. 2003). Wijnands et al. (2001) realized that those systems are excellent targets to study the effects of accretion on the behavior of neutron stars by observing them in quiescence. The accreting material is expected to have a larger effect on the neutron stars in such systems than on the neutron stars in short-duration transients (Wijnands et al. 2001; Rutledge et al. 2002). In the latter systems, the crust is only marginally heated during the outbursts and will quickly return to thermal equilibrium with the core after the end of the outbursts. In the quasi-persistent transients, however, the crust is heated to high temperatures and becomes significantly out of thermal equilibrium with the core (Rutledge et al. 2002). After the end of the prolonged outbursts, it will cool until it returns to equilibrium with the core. The exact cooling time depends on the thermal conductivity of the crust, the core cooling processes, and the accretion history of the source.

KS 1731–260 was the first quasi-persistent transient to be studied in detail in quiescence. It was observed using *Chandra* shortly after the end of its ∼12.5 year outburst (Wijnands et al. 2001) and it was found to have a luminosity of $\sim 10^{33}$ erg s^{-1} (for a distance $d = 7$ kpc; 0.5–10 keV). Half a year later it was observed with *XMM-Newton* and it was found that its luminosity had decreased by a factor of 2–3 (Wijnands et al. 2002b). Using the cooling curves calculated by Rutledge et al. (2002), this drop in brightness can be explained if the neutron star has a large crustal conductivity and enhanced core cooling processes. In

September 2001, a second quasi-persistent neutron-star transient (MXB 1659–29) turned off after having accreted for ∼2.5 years. Wijnands et al. (2003) obtained a *Chandra* observation of this source within a month after the end of its outburst and detected it at a luminosity of $\sim 3-4\times10^{33}$ erg s^{-1} (0.5–10 keV; d = 10 kpc). Several years before this outburst, the source was observed with *ROSAT*, but could not be detected (Verbunt 2001). The flux upper limit was ∼10 times lower than the *Chandra* flux (Oosterbroek et al. 2001; Wijnands 2002). Wijnands et al. (2003) concluded that during the *Chandra* observation the observed radiation was due to a hot crust and not associated with the core.

2. Observations, analysis, and results

Chandra observed MXB 1659–29 twice for ∼27 ksec: on October 15, 2002 (the 2002 observation), and on May 9, 2003 (the 2003 observation). We also used the ∼19 ksec observation performed on October 15–16, 2001 (the 2001 observation; Wijnands et al. 2003). During all observations the ACIS-S3 chip was used. The data were reduced and analyzed using CIAO 3.0. To make use of the latest calibration products, we reprocessed the 2001 observation. A minor background flare occurred during the 2003 observation (factor of ∼2; lasting ∼2 ksec). Its effect on the quality of the source data was negligible and we did not to remove this flare from the data. No flares occurred during the other observations.

For each observation, we extracted the number of source photons, the light curve, and the spectrum, using a circle with a radius of 3″ as source extraction region and an annulus with an inner radius of 7″ and an outer radius of 22″ as background region. We detected 948±31, 263±16, and 107±10 counts (0.3–7 keV; background corrected) for the 2001, 2002, and 2003 observations, respectively, resulting in corresponding count rates of 0.050±0.002, 0.0097±0.0006, and 0.0039±0.0004 counts s^{-1}. Wijnands et al. (2003) observed an eclipse and dipping behavior during the 2001 observation (similar to the outburst behavior of the source; Lewin 1979; Cominsky et al. 1983; Cominsky & Wood 1984, 1989). To search for eclipsing behavior during the 2002 and 2003 observations, we determined the orbital phase range covered by those observations using the time of the eclipse in the 2001 observation as the reference time. Given the orbital phase range traced during each observation, we expect to see a single eclipse per observation and, as anticipated, we did not detect any photons during the expected eclipse intervals. However, we also found that no photons were detected during several time intervals (of equal duration as the lengths of the eclipses) at different phases of the orbital period. Therefore, without prior knowledge of the eclipsing nature of MXB 1659–29, we could not have concluded that we saw eclipses during the 2002 and 2003 observations. Owing to the limited statistics of the 2002 and 2003 observations,

no conclusions can be drawn about possible dipping behavior during these observations.

When extracting the spectra, we used all data, including those taken during the intervals of eclipses and possible dipping behavior. The eclipses could not be removed from the data before extracting the spectra because the uncertainties in the ephemeris presented by Oosterbroek et al. (2001) are sufficiently large so that the exact start and end times of the expected eclipses could not be determined. Instead we decreased the exposure time in the resulting spectral files by 900 s since the eclipse duration during outburst was found to be ∼900 s (Wachter et al. 2000) and Wijnands et al. (2003) reported an eclipse duration of 842±90 seconds for the 2001 observation. Small differences in the eclipse duration might be present between the observations but the expected effects on the resulting fluxes will be marginal. We also did not remove the data obtained during the dipping interval observed in the 2001 observation. Such dipping intervals are likely present during the other two observations but they cannot be identified in the light curves due to limited statistics. For those two observations all data had to be used and to obtain a homogeneous data selection across observations, we included the dipping interval observed during the 2001 observation. Wijnands et al. (2003) found evidence that this dipping behavior is likely due to a change in internal absorption in the system and not due to actual changes in the neutron-star properties. Therefore, the inclusion of the (possible) dipping intervals will likely result in a somewhat higher column density ($N_{\rm H}$) in the spectral fits than the true interstellar $N_{\rm H}$ toward the source, but should not significantly impact other source properties.

We grouped the spectra in bins of 15 counts to validate the use of the χ^2 fitting method and simultaneously fitted the three spectra using Xspec (Arnaud 1996). A variety of one-component models[1] could fit the individual spectra satisfactorily, but since we expect that the X-rays from MXB 1659–29 are due to the cooling of the neutron-star surface, for this paper we only fit the data using a neutron-star hydrogen atmosphere model (NSA; for weakly magnetized neutron stars; Zavlin et al. 1996). In such models the normalization is given by $1/d^2$, with d in pc. The distance should be constant between observations and therefore we left the normalization tied among the different spectra (when leaving the normalizations free between observations, we find that they are consistent with each other). We expect the $N_{\rm H}$ toward the source to be very similar between observations (only minor variations are expected due to variable internal absorption) and this parameter was also tied. We assume

[1]E.g., a power-law model could fit the spectra but with an index of 4.7–5.8 suggesting soft thermal spectra. We also fitted a NSA plus power-law model to determine the upper-limits on the contribution of such a power-law tail to the 0.5–10 keV flux. Those limits are <20%–25%, <35%–45%, and <50%–100%, for the 2001, 2002, and 2003 observation, respectively. The range of upper limits is due to the range assumed in photon indices (between 1 and 2).

a 'canonical' neutron star with a radius of 10 km and a mass of 1.4 $M_\odot$.

From the fits, we found that the normalization was $1.4^{+2.2}_{-0.8} \times 10^{-8}$ which yields a source distance of 5–13 kpc. This is consistent with the distance range given in the literature (10–13 kpc; Oosterbroek et al. 2001; Muno et al. 2001). However, we found that the errors on the fit parameters were dominated by the large uncertainties in the normalization and did not allow us to realize the full potential of the data. If the source distance were established through an independent method, we could fix the normalization in the NSA models, resulting in considerably smaller errors on the remaining fit parameters. Therefore, instead of leaving the normalization as a free parameter, we fixed it so that it corresponded to a distance of 5, 10, and 13 kpc, covering the full range of allowed distances obtained when the normalization was a free parameter. To estimate the bolometric fluxes ($F_{\rm bol}$) we extrapolated the model to the energy range 0.01–100 keV which gives approximate bolometric fluxes[2]. To calculate the flux errors, we fixed each free fit parameter (only one at a time) either to its minimum or maximum allowed value. After that we refitted the data and recalculated the fluxes. This process was repeated for each free parameter and the final flux range determined the flux errors. The fit parameters obtained are listed in Table 1.

This table shows that $T_{\rm eff}^{\infty}$ and $F_{\rm bol}$ decreased in time (Fig. 2). We fitted the $T_{\rm eff}^{\infty}$ and $F_{\rm bol}$ curves with an exponential decay function $y(t) = c_0 e^{-\frac{t-t_0}{\tau}}$, with c_0 a normalization constant, t_0 the start time, and τ the e-folding time. We found that the other fit parameters were not very sensitive to the value of t_0, but when t_0 was left free it had adverse effects on the errors on those parameters. Therefore, we fixed t_0 to MJD 52159.5 which corresponds to midday September 7, 2001 (the last day MXB 1659–29 was found to be active; Wijnands et al. 2002a) and which can be regarded as an approximation of the time when $T_{\rm eff}^{\infty}$ and $F_{\rm bol}$ began to decrease. The assumed exponential functions could adequately describe the decrease in $T_{\rm eff}^{\infty}$ and $F_{\rm bol}$ (Fig. 2; alternative functions did not provide adequate fits). We found that τ and c_0 for the $F_{\rm bol}$ curve were 289±37, 262±33, and 254±29 days, and 70±9, 48±6, and 43±6 $\times 10^{-14}$ erg cm^{-2} s^{-1}, when assuming a distance of 5, 10, or 13 kpc, respectively, in the spectral fits. The corresponding τ and c_0 for the $T_{\rm eff}^{\infty}$ curve were 1153±160, 1060±126, and 1055±112 days, and 0.099±0.004, 0.126±0.004, and 0.139±0.004 keV. We saw no evidence that the curves approached a rock-bottom value: we found an upper limit on such a value

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[2]We verified that the 0.01–100 keV fluxes approximate $F_{\rm bol}$ by calculating the bolometric luminosity $L_{\rm bol} = 4\pi\sigma R_{\infty}^2 T_{\rm eff}^{\infty 4}$, with σ Stefan-Boltzmann constant, $T_{\rm eff}^{\infty}$ the effective temperature (at infinity), and R_{∞} the neutron-star radius (at infinity). The 0.01–100 keV fluxes were indeed consistent with the calculated $F_{\rm bol}$. We use the measured fluxes because their errors takes into account the uncertainties in $N_{\rm H}$ and the $T_{\rm eff}^{\infty}$ obtained for all observations. The $L_{\rm bol}$ errors are only calculated using the $T_{\rm eff}^{\infty}$ errors during one specific observation.

of 3.5–7.5 $\times 10^{-14}$ erg cm^{-2} s^{-1} for the $F_{\rm bol}$ curve (resulting in bolometric luminosity limits of 2.2–7.0 $\times 10^{32}$ erg s^{-1}), and 0.06–0.07 keV for the $T_{\rm eff}^{\infty}$ curve.

3. Discussion

We have presented monitoring *Chandra* observations of MXB 1659–29 in quiescence. The first observation was taken only a month after the end of its last outburst which lasted 2.5 years; the second and third observations were taken ∼1 and ∼1.5 years after this initial one. Because it is expected that the emission should be dominated by thermal emission from the hot neutron-star crust (see Wijnands et al. 2003), we fitted the data with a NSA model for weakly ($B < 10^{8-9}$ G) magnetized neutron stars. We found that $F_{\rm bol}$ decreased by a factor of ∼8 in ∼1.5 years and the rate of decrease followed an exponential decay function. Furthermore, $T_{\rm eff}^{\infty}$ also decreased and the rate of decrease again followed an exponential decay function. We found that the e-folding time of the $T_{\rm eff}^{\infty}$ curve was consistent with four times that of the $F_{\rm bol}$ curve, as expected if the emission is caused by a cooling black body for which the bolometric luminosity is given by $L_{\rm bol} = 4\pi\sigma R_{\infty}^2 T_{\rm eff}^{\infty 4}$ (see footnote 2): if $T_{\rm eff}^{\infty}$ decays exponentially, $L_{\rm bol}$ (and thus $F_{\rm bol}$) will also decay exponentially but with an e-folding time four times smaller than that of $T_{\rm eff}^{\infty}$, exactly what we observe.

Our results support the suggestion that the crust was heated to high temperatures during the prolonged accretion event, which ended a month before our first observation, and that it is now cooling until it reaches thermal equilibrium with the core. Rutledge et al. (2002) calculated cooling curves for the neutron star in KS 1731–260, assuming different behaviors of the crustal micro-physics and the core cooling processes. Those curves can be used as a starting point to investigate how our results of MXB 1659–29 could be explained. Of those curves, only the one which assumes a large crustal conductivity and the presence of enhanced core cooling processes exhibits a large luminosity decrease in the first two years after the end of the last outburst, suggesting that the neutron star in MXB 1659–29 has similar properties. This conclusion was already tentatively reached by Wijnands et al. (2003) based on a comparison of the luminosity seen during the October 2001 *Chandra* observation with the significantly lower luminosity upper-limit found with *ROSAT*. But detailed cooling curves for the neutron star in MXB 1659–29 need to be calculated to fully explore (and exploit) the impact of our observations on our understanding of the structure of neutron stars. The cooling curves calculated by Rutledge et al. (2002) for KS 1731–260 only give us a hint of the behavior of MXB 1659–29 because they depend on the long-term ($> 10^4$ years) accretion history of the source. For KS 1731–260, this long-term accretion behavior was quite unconstrained due to large uncertainties in the averaged duration of the outbursts,

the time-averaged accretion rate during the outbursts, and the time the source spent in quiescence. However, the accretion history of MXB 1659–29 over the last three decades is much better constrained (Wijnands et al. 2003), which will help to reduce the uncertainties in its long-term averaged accretion history allowing for more detailed cooling curves to be calculated for MXB 1659–29. This might help to constrain the physics of the crust better for MXB 1659–29 than for KS 1731–260. The only significant uncertainty left is that of the source distance; however, we found that this only affects the exact values of the bolometric fluxes and the effective temperatures, but not their rate of decay.

Our 0.5–10 keV flux during the May 2003 *Chandra* observation is still higher than the upper limit found with *ROSAT*, suggesting that the crust will cool even further in quiescence and that we have not yet reached thermal equilibrium between the crust and core. Further monitoring observations are needed to follow the cooling curve of the crust to determine the moment when the crust is thermally relaxed again. When this occurs, no significant further decrease of the quiescent luminosity is expected and from this bottom level the state of the core can be inferred. As of yet, we have found no evidence that the flux and temperature are reaching a leveling-off value, associated with the temperature of the core, although the limits we obtained are not very stringent.

Jonker, Wijnands, & van der Klis (2004) suggested that the difference in luminosity of MXB 1659–29 between the *ROSAT* non-detection and the 2001 *Chandra* observation might be due to differences in residual accretion rate onto the surface. Residual accretion could indeed produce soft spectra (e.g., Zampieri et al. 1995), but to explain the exponential decay we observe for $F_{\rm bol}$ and $T_{\rm eff}^{\infty}$, the residual accretion rate must also decrease exponentially with a timescale of a year. Although this cannot be completely ruled out, we believe this is unlikely since other neutron-star transients have been observed to reach their quiescent states on timescales of only tens to several tens of days at the end of their outbursts (e.g., Campana et al. 1998b; Jonker et al. 2003) and the variations in accretion rate tend to be more stochastic. Moreover, if the neutron star has a significant magnetic field strength, this might inhibit material from reaching the surface when accreting at the inferred low rates.

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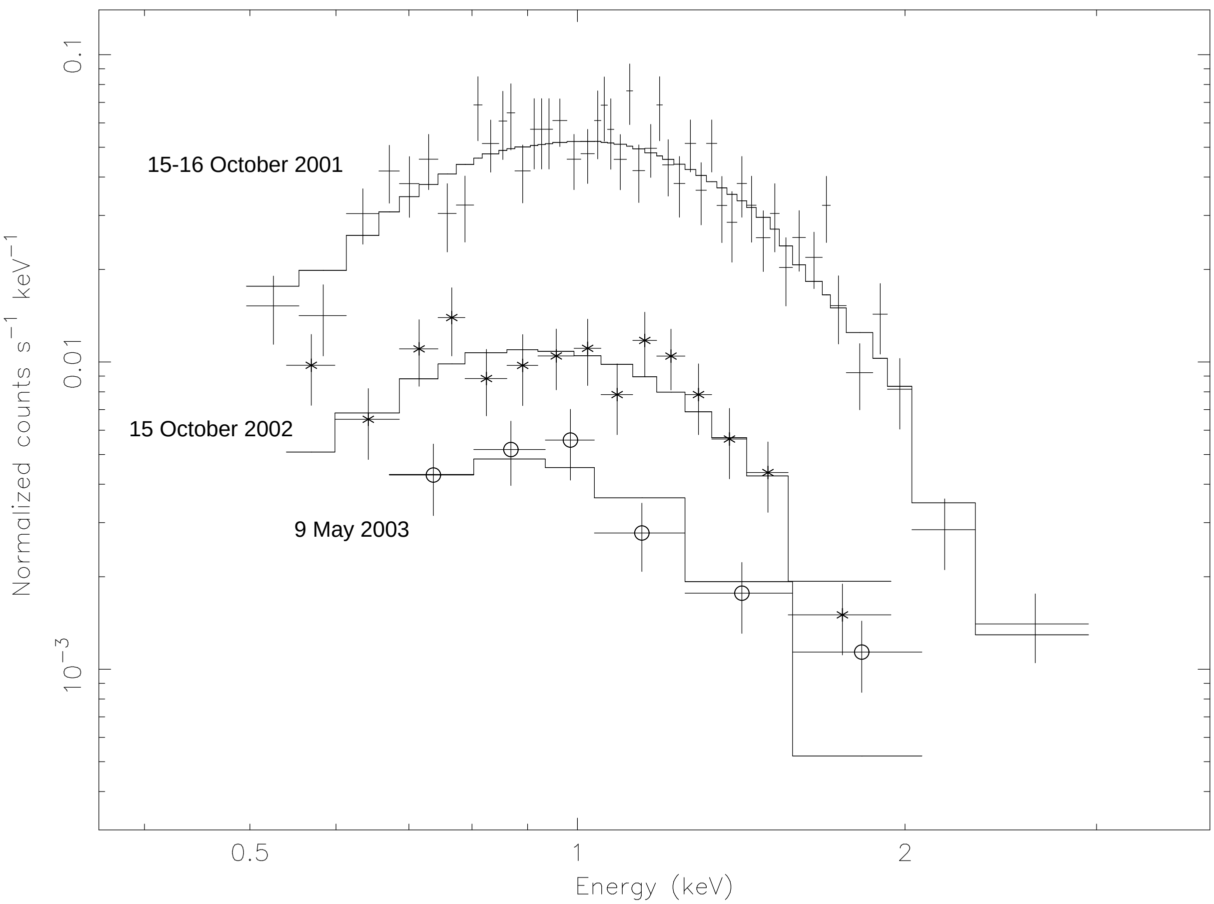

Fig. 1.— The *Chandra* X-ray spectra obtained during the quiescent state of MXB 1659–29. The top spectrum was obtained on October 15–16, 2001, the middle spectrum (indicated by the crosses) was obtained on October 15, 2002, and the bottom spectrum (indicated by the open circles) was obtained on May 9, 2003. The solid lines through the spectra indicate the best fit neutron-star hydrogen atmosphere model (that of Zavlin et al. 1996; for weakly magnetized neutron stars).

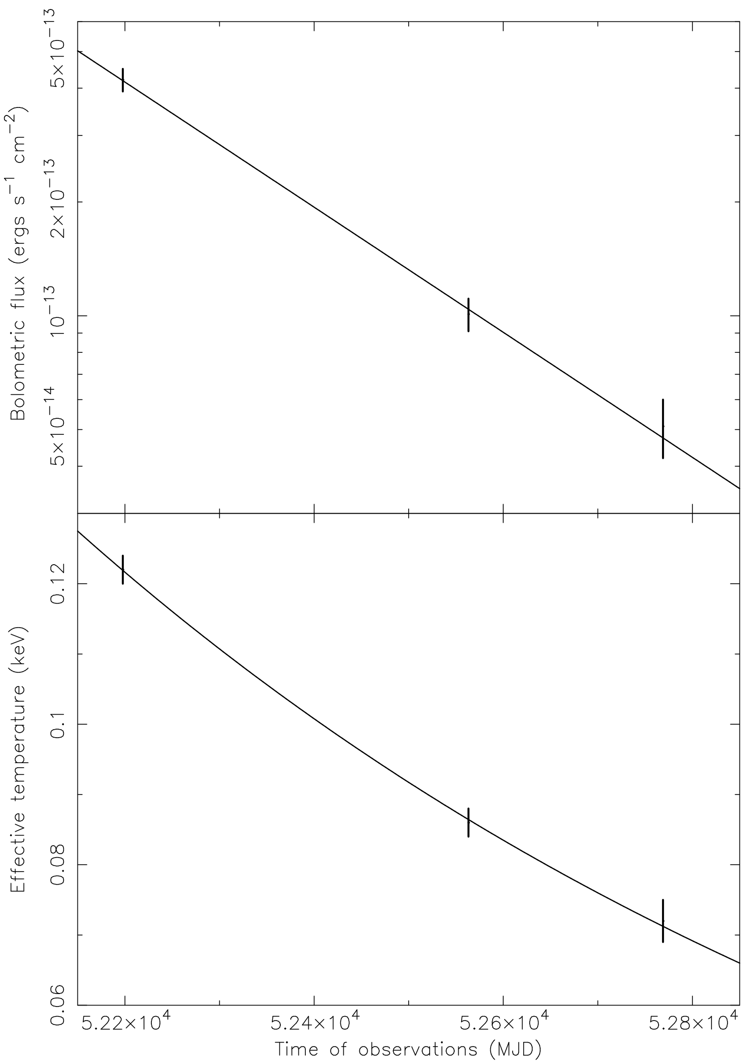

Fig. 2.— The bolometric flux (top panel) and effective temperature (bottom panel; for an observer at infinity) of the neutron-star crust as a function of time (as obtained with the neutron-star hydrogen atmosphere model for weakly magnetized neutron stars of Zavlin et al. 1996). The solid curves are the best fit exponential function through the data points. The bolometric fluxes are plotted on a logarithmic scale, but for clarity, the effective temperatures are plotted on a linear scale. The data used in this figure are those obtained when assuming a distance of 10 kpc in the spectral fits; the figures for a distance of 5 or 13 kpc are very similar and therefore we omit them. Only the absolute values of the bolometric flux and effective temperature are different but the overall decay trend is nearly identical.

Table 1. Spectral results for MXB 1659–29

Parameter	Distance assumed		
	5 kpc	10 kpc	13 kpc
$N_{\rm H}$ (10^{21} cm^{-2})	2.8±0.3	1.8±0.2	1.5±0.2
$kT_{\rm eff}^{\infty}$ (keV)			
2001	0.096±0.002	0.122±0.002	0.134±0.002
2002	0.069±0.002	0.086±0.002	$0.094^{+0.002}_{-0.003}$
2003	0.059±0.002	0.072±0.003	0.079±0.003
Flux (10^{-14} erg cm^{-2} s^{-1}; 0.5–10 keV; unabsorbed)			
2001	41.8±3.2	31.3±2.3	28.4±2.1
2002	9.1±1.0	$6.4^{+0.8}_{-0.6}$	5.7±0.6
2003	$4.0^{+0.8}_{-0.2}$	$2.8^{+0.7}_{-0.5}$	2.5±0.4
Bolometric flux (10^{-14} erg cm^{-2} s^{-1}; unabsorbed)			
2001	61.6±4.2	42.1±2.9	37.7±2.8
2002	16.9±1.5	10.1±1.0	8.5±0.8
2003	$8.9^{+1.4}_{-0.4}$	5.1±0.9	4.2±0.6
χ^2/d.o.f.	59.2/65	56.1/65	58.6/65

Note: The error bars represent 90% confidence levels. We used a neutron-star mass of 1.4 $M_\odot$ and radius of 10 km and the neutron-star hydrogen atmosphere model for weakly magnetized neutron stars of Zavlin et al. 1996.